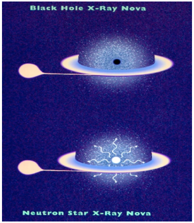
Astrophysics of Double Neutron Star Binaries

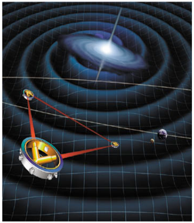


Chris Belczynski[1,2,3]

[1] Department of Astronomy
New Mexico State University

[2] Tombaugh Fellow

[3] LIGO Scientific Collaboration



Sixth International LISA Symposium: June 22, 2006

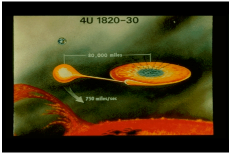
Population Synthesis: The Method

Population synthesis is a Monte Carlo method which allows to evolve large stellar ensembles (both single and binary stars):

- start with initial conditions
- follow single and binary evolution
- calibrate results
- extract your population

In the end synthetic populations are generated:

- statistical analysis
- comparisons with observations
- finally, specific predictions

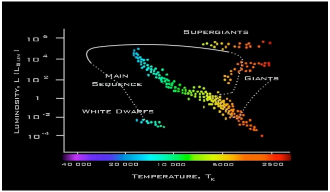


StarTrack: Single Star Evolution

Stars are evolved from the onset of nuclear burning.

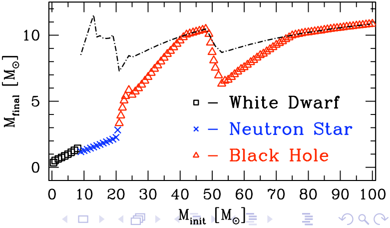
Evolution depends on:

- initial mass ($M_{\rm init}$)
- chemical composition
- mixing (overshooting)
- stellar winds



... and in the end stars form compact remnants:

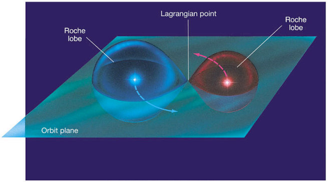
- white dwarfs ($M_{\rm init} \lesssim 8{\rm M}_\odot$)
- neutron stars ($8 \lesssim M_{\rm init} \lesssim 20{\rm M}_\odot$)
- black holes ($M_{\rm init} \gtrsim 20{\rm M}_\odot$)

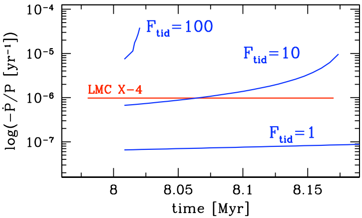


StarTrack: Binary Evolution

Evolution of binary systems is complex and some processes are still not fully understood. The input physics key ingredients are:

- tidal interactions
- mass transfer phases
  - rejuvenation
  - orbit evolution
  - common envelope
- supernova explosions
  - mass loss/natal kicks
  - full orbital solution
- ang. momentum losses
  - systemic mass loss
  - magnetic braking
  - gravitational radiation





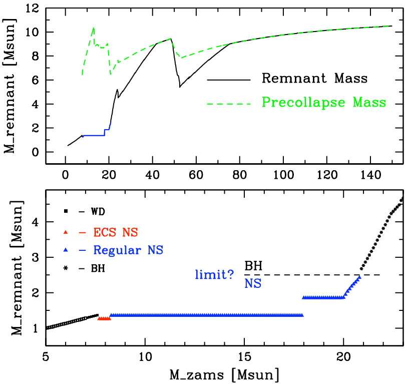
NS Star Masses

Modeling:

- $\sim 1.35 M_{\odot}$: $M_{\rm zams} < 18 M_{\odot}$
- $\sim 1.8 M_{\odot}$: $M_{\rm zams} > 18 M_{\odot}$
- $\sim 1.26 M_{\odot}$: ECS NS ($M_{\rm zams} \sim 8 M_{\odot}$)

Observations:

- $\sim 1.2 - 1.4 M_{\odot}$: double pulsars
- $\sim 1.9 M_{\odot}$: Vela X-1 pulsar
- $\sim 2.1 M_{\odot}$: PSR J0751+1807



What is maximum NS mass? (accretion, collapse to BH?)

NS-NS Formation Channels

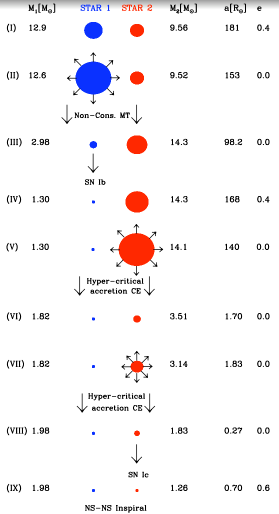
Reanalysis of compact object formation led to
a prediction of new NS-NS population:

- late evolutionary stages ->
- helium star expansion ->
- extra mass transfer episode ->
- if stable RLOF: Classical II if CE: New

New (versus Classical) NS-NS binaries:

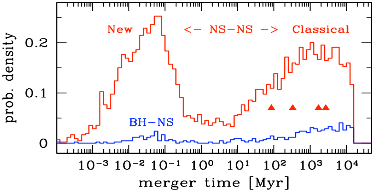
- orbital periods: < 2 hr ($\sim 2-100$ hr)
- merger times: < 1 Myr (~ 1 Gyr)
- merger sites: birth place (far out)

Belczynski & Kalogera 2001
Belczynski, Bulik & Kalogera 2002
Belczynski, Bulik & Rudak 2002
Perna & Belczynski 2002
Ivanova, Belczynski, Kalogera, Rasio & Taam 2003
Belczynski, Perna, Bulik, Kalogera, Ivanova & Lamb 2006



NS-NS: Formation -> Present

Merger times at formation ->



Systems evolve due to emission of GR only:

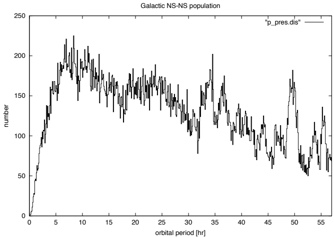
- orbital decay
- circularization

Present population contains only:

- $\sim$ 20% of systems that have formed
- the long-lived systems
  (short-lived systems have merged)

Number of Galactic NS-NS Binaries

- Galactic disk stellar population ($f_0 = 1.0$)
  $M_{\rm MW} \sim 1.5 \times 10^{11} M_\odot$ (2.5×10^{11} stars)
- binary stars ($f_1 = 0.5$)
- massive binaries ($f_2 = 0.003$)
  ($M_a > 5M_\odot, M_b > 4M_\odot$)
- all NS-NS (formation) ($f_3 = 0.002$)
- Current NS-NS population ($f_4 = 0.229$)



$1 - 10^{-4}$ Hz (<5.7hr)	$1 - 5 \times 10^{-5}$ Hz (<11hr)	$1 - 10^{-5}$ Hz (<57hr)
($f_5 = 0.031$)	($f_5 = 0.087$)	($f_5 = 0.404$)
$f_{\rm tot} = 2 \times 10^{-8}$	$f_{\rm tot} = 6 \times 10^{-8}$	$f_{\rm tot} = 29 \times 10^{-8}$
$N_{\rm NS-NS} = 6\,000$	$N_{\rm NS-NS} = 16\,000$	$N_{\rm NS-NS} = 70\,000$

NS-NS: very rare systems, but still many predicted in Galaxy at present!

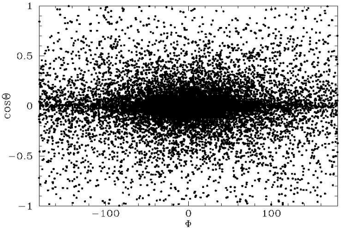
Observable NS-NS Population

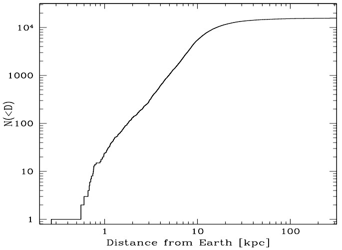
- start with 16 000 NS-NS
- put them in Galactic disk
- follow their trajectories (birth SNe kicks)
- check current positions
- calculate distance from Earth

$\sim$ 20 NS-NS within 1 kpc
$\sim$ 100 NS-NS within 2 kpc

NS-NS with $P_{\rm orb} < 0^{hr}.56$ ($f > 1mHz$):
$\sim$ 15 NS-NS within 20 kpc

not many, but......





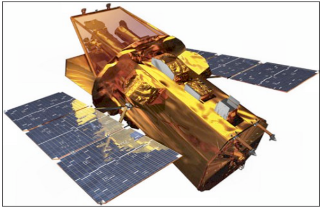
Potential LISA Science

better understanding of NS properties:

- periods: progenitor evolution
- positions: spatial distr./kicks
- distances: NS masses

Improvement on NS-NS merger rates:

- Galactic merger rates
  - empirical: $\sim 3 - 300\ Myr^{-1}$
  - modeling: $\sim 10 - 60\ Myr^{-1}$
- GR detection (LIGO, GEO, VIRGO)
- short/hard GRB progenitors? (SWIFT, HETE-II)

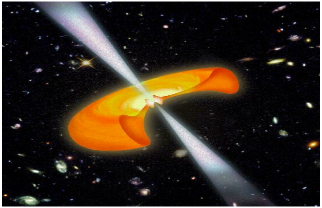


Swift satellite: GRB localization.

Short Gamma-ray Bursts: Observations

Short-hard GRBs:

- several found within z<0.5
- in old ellipticals
- in young star-forming galaxies
- both low- and high-mass hosts



Progenitor issues/problems:

- release of 10^{49} erg within a sec?!
- what are their progenitors?
  - NS-NS/BH-NS mergers
  - magnetars
  - accretion induced collapse

homogeneous progenitor population?!

why not found at higher redshifts?!

Short Gamma-ray Bursts: Modeling

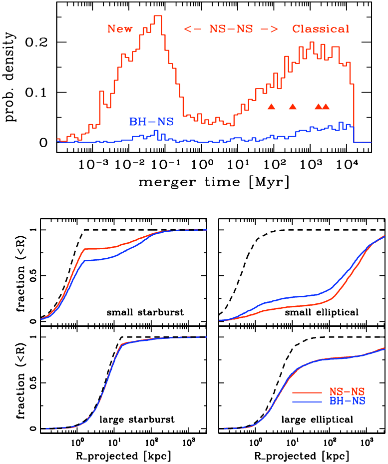
New NS-NS || Classical NS-NS:

- all redshifts || low-intermediate
- in starbursts || in ellipticals
- inside/outskirt || outskirt/outside

(Mixed populations in spiral hosts)

Open questions:

- if more GRB found in small ellipt.
  lower natal kicks in binaries?
- if no GRB found at $z \sim 3-5$
  no New NS-NS: no CE survival?
- if no GRB found at $z \sim 1-2$
  how do we explain Galactic NS-NS?!



(Belczynski et al. 2006)

Short Gamma-ray Bursts: Conclusions

- Compact object mergers can explain
  - presence of GRBs in both: old and young galaxies
  - their locations with respect to hosts (lower kicks?)
- Potential problem with the lack of higher redshift GRBs
  - unless some are already observed
    (e.g., GRB 060121 , $z \sim 1.7 - 4.6$)
  - any bias against detecting them at higher z?
    (not upto $z \sim 1 - 2$)
  - or some process preventing NS-NS formation at high z?
    (but what?!)

or if nothing of the above works, NS-NS is not a GRB progenitor.....

Summary

NS-NS are relatively small Galactic population. Only $\sim$ tens of close (to Earth) NS-NS systems as compared to hundreds of NS-WD and thousands of WD-WD binaries.

However, even with tens of detections we increase statistics for NS-NS binaries by an order of magnitude. And we improve:

- understanding of NS-NS formation physics
  - NS masses (accretion/recycling)
  - progenitor evolution (e.g., kicks)
- estimates of merger rates
  - ground based GR detection prospects?
  - short-hard GRB progenitors?

Finally, BH-NS and BH-BH systems are not predicted to form in numbers sufficiently large to grant detection with LISA.